Overview of the EOS Aura Mission

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Abstract
Aura, the last of the large EOS observatories, was launched on July 15, 2004. Aura is designed to make comprehensive stratospheric and tropospheric composition measurements from its four instruments, HIRDLS, MLS, OMI and TES. With the exception of HIRDLS, all of the instruments are performing as well or better than expected, and even HIRDLS will likely be able to deliver most of their planned data products. We summarize the mission, instruments and synergies in this article.

1.0 Introduction

The Earth Observing System (EOS) Program began in the late 1980's with the selection of a large number of earth science instruments and interdisciplinary science teams. Originally conceived to fly on two very large platforms (EOS A and B), budget constraints forced the redesign of EOS program. EOS now consists of three core platforms, Terra, Aqua and AURA and several smaller satellites such as SORCE and IceSAT. Terra (formerly EOS AM), launched in late 1999, focuses on land processes. Aqua (formerly EOS PM) focuses on the atmosphere's hydrological cycle was launch in early 2002. Aura (Latin for breeze, formerly EOS CHEM) concentrates on atmospheric composition. Aura was launched July 15, 2004 into an ascending node 705 km sun-synchronous polar orbit with a 98º inclination with an equator-crossing time of 13:45±15 minutes. . The design life is five years with an operational goal of six years. Aura flies in formation about 15 minutes behind Aqua. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO, http://www-calipso.larc.nasa.gov/) and Cloudsat, to be launched together in spring 2005, [Stephens et al., 2002, http://cloudsat.atmos.colostate.edu/] will fly a few minutes behind Aqua. This group of satellites, including the CNES PARASOL satellite (http://smsc.cnes.fr/PARASOL/GP_mission.htm), which was launched in December 2004, and the ESSP Orbiting Carbon Observatory (OCO, http://oco.jpl.nasa.gov/), scheduled for launch in 2008, are referred to as the "A-Train." The measurements from Aura will be within 30 minutes of these other platforms. The A-Train can be thought of as a extended instrument package focusing on climate change.

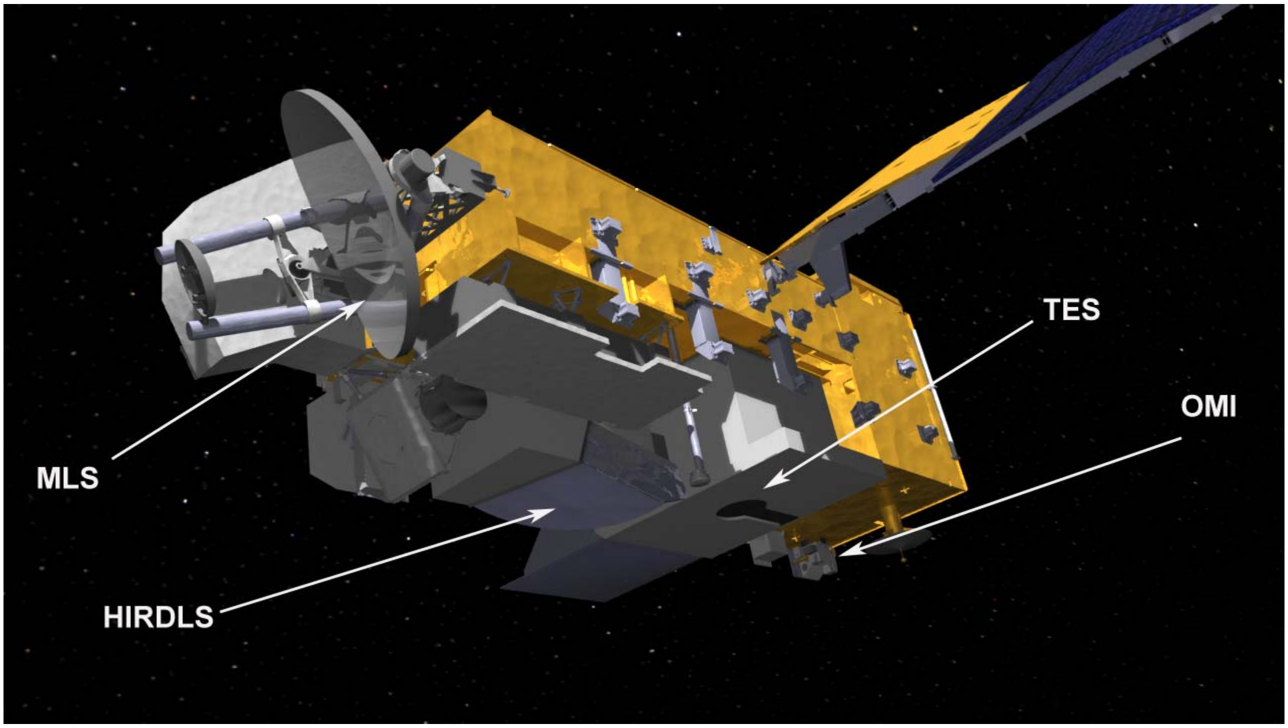

Figure 1, Computer generated model of the Aura spacecraft showing the location of the four instruments, HIRDLS, MLS, OMI and TES.

Figure 1 shows the Aura spacecraft and its four chemistry instruments (Table 1): the High Resolution Dynamics Limb Sounder (HIRDLS), the Microwave Limb Sounder (MLS), the Ozone Monitoring Instrument (OMI) and the Tropospheric Emission Spectrometer (TES). These instruments were selected because (1) their complimentary measurements (2) their technological heritage and (3) the new capabilities they bring to measuring the earth's atmosphere. Below we describe the objectives and science strategy of the Aura mission.

TABLE 1 – Aura Instruments and Measurements

Acronym	Name	Instrument PI	Constituent	Instrument Description
HIRDLS	High Resolution Dynamics Limb Sounder	John Gille, National Center for Atmospheric Research & U. of Colorado; John Barnett, Oxford University	Profiles of T , O_3, H_2O, CH_4, N_2O, NO_2, HNO_3,, N_2O_5, CF_3Cl, CF_2Cl_2,$ClONO_2$, Aerosols	Limb IR filter radiometer from 6.2μ to 17.76μ 1.2 km vertical resolution up to 80 km.
MLS	Microwave Limb Sounder	Joe Waters, Jet Propulsion Laboratory	Profiles of T, H_2O, O_3, ClO, BrO, HCl, OH, HO_2, HNO_3, HCN, N_2O, CO, Cloud ice.	Microwave limb sounder 118 GHz to 2.5 THz 1.5-3 km vertical resolution
OMI	Ozone	Pieternel	Column O_3, SO_2,	Hyperspectral nadir

	Monitoring Instrument	Levelt, KNMI, Netherlands	aerosols, NO_2, BrO, OClO. HCHO, UV-B, cloud top pressure, O_3 profiles.	imager, 114° FOV, 270-500 nm, 13x24 km footprint for ozone and aerosols
TES	Tropospheric Emission Spectrometer	Reinhard Beer, Mike Gunson, Jet Propulsion Laboratory	Profiles of T, O_3, NO_2, CO, HNO_3, CH_4, H_2O.	Limb (to 34 km) and nadir IR Fourier transform spectrometer 3.2-15.4μ Nadir footprint 5.3x8.5 km, limb 2.3 km

2.0 Science Objectives of the Aura Mission

The objective of the Aura mission is to attack three principal science questions: Is the ozone layer changing as expected? What are the processes that control tropospheric pollutants, and do we understand the transport of trace gases between the troposphere and the stratosphere? What is the role of upper tropospheric aerosols, water vapor and ozone in climate change? The strategy Aura will employ in answering these questions is to obtain a very complete set of chemical observations at high vertical and horizontal resolution throughout the atmosphere (Table 1). These measurements, when combined with field campaigns, other satellite measurements (e.g. Aqua measurements 15 minutes ahead of Aura on roughly the same ground track), and ground based instruments, should provide unprecedented insights into the chemical and dynamical processes associated with our atmosphere. In the section below we will discuss the individual questions and the Aura measurement approach.

2.1 Is the ozone layer changing as expected?

Total Ozone Mapping Spectrometer (TOMS) Observations from 1978 to the present show strong secular trends in decreasing ozone both at midlatitudes and at the polar regions, Although the Antarctic ozone hole growth has slowed, very significant ozone depletions have occurred in the Arctic [Newman et al., 1997, WMO 2002]. As a result of international agreements, tropospheric chlorofluorocarbons concentrations have begun to decrease. Upper Atmosphere Research Satellite (UARS) data shows a flattening in the stratospheric chlorine reservoir concentrations [Anderson et al., 2000] although an unambiguous decrease has not been detected. A decrease in chlorine should lead to recovery of the ozone layer, but this recovery may be delayed by increases in greenhouse gases which would (1) cool the stratosphere giving rise to more frequent and persistent polar stratospheric clouds (see Solomon [1999] for a discussion of the chemistry of the ozone hole) and/or increase the water vapor in the stratosphere by warming the tropical tropopause [WMO, 2002]. In fact, stratospheric water vapor does appear to be increasing faster than can be accounted for by the secular trend in methane. As a result of the uncertainty in stratospheric trace gas, current models used to assess the ozone layer do not agree on the timing of the recovery [WMO, 2002].

Recovery of ozone is the primary science question for the instruments HIRDLS, MLS and OMI. The stratospheric measurements made by these instruments will permit a very complete assessment of the chemical processes controlling ozone. All three of the major radicals that destroy ozone

(ClO, OH and NO) will be made by HIRDLS and MLS along with the main reservoir gases, HCl, $ClONO_2$ and HNO_3. In addition, the Aura instrument payload will make measurements of of chlorine and nitrogen sources gases as well as long lived tracers of motion, N_2O, H_2O, and CH_4. OMI continues the column and profile ozone trends from TOMS/SBUV with higher horizontal resolution.

2.2 What are the processes that control tropospheric pollutants?

Human activities have increased surface-level ozone concentrations and decades of research and regulations now reveal that a global approach is required to further understand the sources of ozone and other pollutant precursors. Tropospheric ozone production occurs when volatile organic compounds (VOCs) and nitrogen oxides (NO_x) are exposed to sunlight. Since the emissions of these ozone precursors are directly linked to today's urban and industrial lifestyle, reductions are both socially and economically costly. For this reason, policymakers have sought guidance from the scientific community in determining effective ways to meet health-based ozone standards or goals. The response of ozone to changes in VOC and NO_x emissions can be quite complex and variable. Moreover, winds can transport both ozone and its precursors over large distances; and, as a result, exposure to elevated ozone can arise from both local and distant sources. The Aura mission is designed to produce the first global assessment of tropospheric ozone, its precursors and controlling gases. The measurements from TES as well as measurements from OMI (NO_2, ozone and aerosols) combined will provide important data on this process.

2.3 Do we understand the transport of trace gases between the troposphere and the stratosphere and the role of upper tropospheric aerosols, water vapor and ozone in climate change?

The importance of the upper troposphere/lower stratosphere (UT/LS) in chemistry and climate problems is well stated in a number of international assessment documents [i.e. Houghton et al., 1995]. Within the context of chemical problems one of the largest uncertainties is how much ozone and odd nitrogen is supplied to the troposphere from the stratosphere [Hauglustine et al., 1998]. Even estimates of the cross tropopause flux of ozone from the stratosphere are uncertain to within 15% or greater [Gettelman et al., 1997]. There are fundamental climate change questions related to moistening or drying of the upper troposphere as convective activity changes. For example, it is now understood that the IR cooling of the atmosphere is strongly influenced by upper tropospheric/ lower stratospheric water vapor, aerosols and ozone [Houghton et al., 1995]. On decadal time scales, signals from greenhouse gas changes and signals from the changes in reactive constituents are intertwined and difficult to untangle. The tropopause is a complex internal boundary within the atmosphere related to both radiative and dynamical mechanisms [Thuburn and Craig, 1997]. Because the concentrations of many trace gases vary greatly across the tropopause, changes in the UT/LS impact not only the radiative attributes of the atmosphere, but also the chemical environment.

The location and intensity of both tropical and mid-latitude strat-trop exchange is key to our ability to quantify the properties of the UT/LS. One of the major science questions Aura measurements will be needed to solve is the mystery of increasing stratospheric water vapor. Stratospheric water vapor concentrations are increasing faster than can be accounted for by increases in methane (the major in situ source of water vapor in the stratosphere. A number of hypothesis suggest that changes in the freeze-dry mechanism at the tropical tropopause are producing an increase in water transport into the stratosphere. Untangling the complex free-dry mechanism of the tropical tropopause will be one of the goals of the Aura science team. Relative to the upper troposphere/ lower stratosphere dynamics and chemistry, Aura instruments will make key measurements of ozone, water vapor, ice particles and long lived trace gases that will give lead to a better understanding of the dynamics and chemistry of that region. Especially important to the measurements of the UT/LS is HIRDLS which can make high horizontal and vertical resolution mesurements of the atmospheric limb.

3.0 Spacecraft and Instrument descriptions

The Aura spacecraft is designed for a six-year lifetime. The spacecraft orbits at 705 km in a sun-synchronous orbit (98^o inclination) with a 1:45 PM ±15 minute equator crossing time. Aura limb instruments are all designed to observe roughly along the orbit plane. MLS is on the front of the spacecraft (the forward velocity direction) while HIRDLS, TES and OMI are mounted on the nadir side. HIRDLS and TES will make limb soundings observing backward while MLS will make limb sounds observing forward. OMI and TES will make nadir soundings as shown in Figure 2. The advantage of this instrument configuration is that each of the instruments can observe the same air mass within seconds.

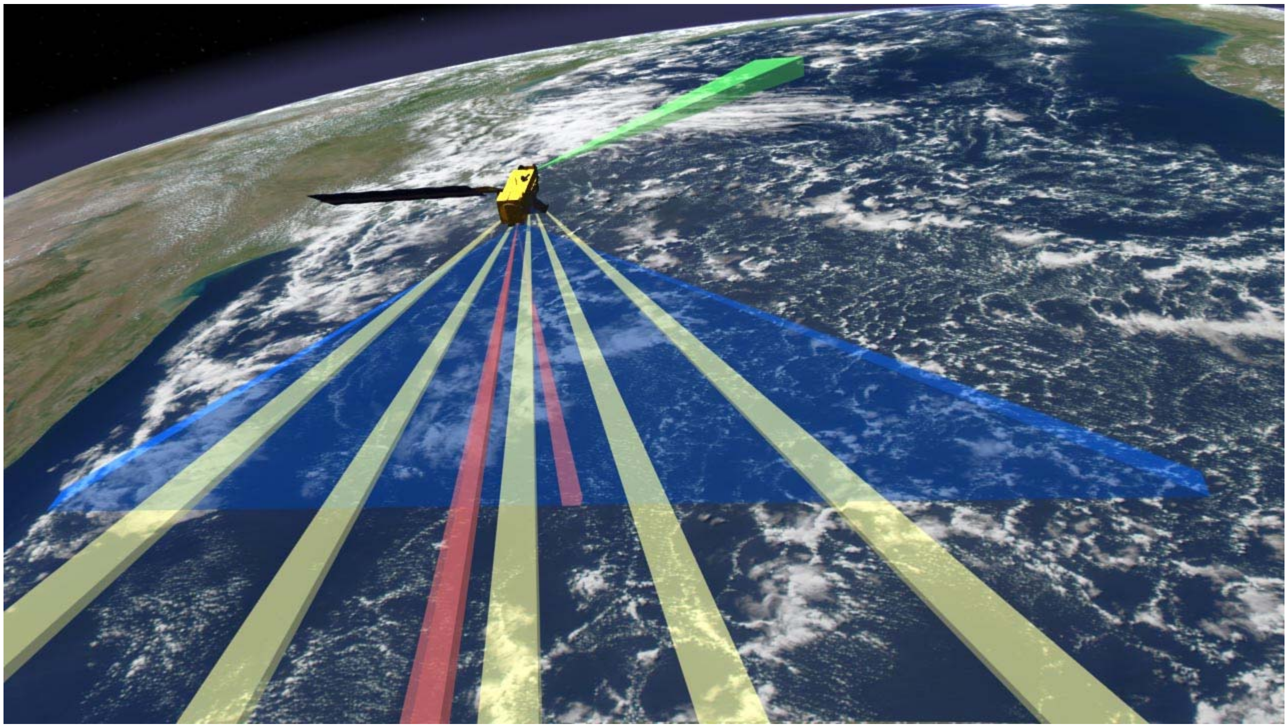

Figure 2. Aura instrument fields of view are shown as colored beams. The viewer is looking at the back of the spacecraft. MLS performs forward limb sounding (green). OMI nadir measurements are indicated with the blue swath. TES limb and nadir measurements are shown in pink. HIRDLS measurements (5 scan positions) are shown in yellow. TES and HIRDLS measurements are made in the anti-velocity direction.

3.1 HIRDLS

HIRDLS is an infrared limb-scanning filter radiometer designed to make the measurements listed in Table 1 [Gille et al, 1994, Gille and Barnett, 1996]. HIRDLS can also determine the altitude of polar stratospheric clouds and tropospheric cloud tops.

The HIRDLS instrument has a long heritage extending back to Nimbus-4, and will obtain profiles over the entire globe, including the poles, both day and night. Complete Earth coverage (including polar night) can be obtained in 12 hours. High horizontal resolution is obtained with a commandable azimuth scan which, in conjunction with a rapid elevation scan, provides profiles up to 3,000 km apart in an across-track swath. Vertical profiles are spaced every 5° in latitude and longitude. Observations of the lower stratosphere and upper troposphere are improved through the use of special narrow and more-transparent spectral channels. The instrument is programmable; thus, a variety of observation modes can be used, and may be adapted in flight to observe special geophysical events like volcanic eruption clouds or polar stratospheric cloud regions.

The primary advantages of HIRDLS over previous infrared limb instruments (LIMS, SAMS, ISAMS, CLAES) are its high vertical and horizontal resolution and its vertical range which extends from the upper troposphere throughout the stratosphere.

After launch, activation of the HIRDLS instrument revealed that something was blocking the optical path so that only a small portion of the aperture could view the earth’s atmosphere. Engineering studies suggest that a piece of thermal blanketing material ruptured from the back of the instrument during the explosive decompression of launch. This material covers most of the scan mirror. Attempts to remove this material by moving the scan mirror failed. However, even with the 80% blockage, measurements at high vertical resolution can be made at one scan angle. As of this writing, the principal investigators have demonstrated temperature retrievals with the instrument which is the first step in constituent retrievals. HIRDLS will no longer have the horizontal coverage proposed, and with only one side of the aperture available, HIRDLS will not be able to make measurements over the Antarctic.

3.2 MLS

MLS uses microwave emission to measure stratospheric temperature and constituents and upper tropospheric constituents (Table 1) [Waters et al, 1999]. MLS also has unique capability to measure upper tropospheric water vapor in the presence of tropical cirrus, and also the cirrus ice content. Aura MLS continues the successful effort of UARS MLS [Waters et al., 1993] using advanced technology to provide new measurements. These measurements will be especially valuable for diagnosing the potential for severe loss of Arctic ozone during the critical period when abundances of stratospheric chlorine will still be high, and slight cooling of the stratosphere could exacerbate ozone loss due to chlorine chemistry. MLS will make the first global measurements of OH, HO_2 and BrO, constituents that play an important role in stratospheric chemistry. The MLS instrument observes in spectral bands centered near five frequencies [118 GHz (temperature and pressure); 190 GHz (H_2O, HNO_3); 240 GHz (O_3 and CO); 640 GHz, (N_2O, HCl, ClO, HOCl, BrO, HO_2, and SO_2); and 2.5 THz (primarily for OH)].

The MLS instrument aboard UARS has demonstrated the MLS capability of measuring upper tropospheric water vapor profiles [Read et al., 1995; Sandor et al., 1998], knowledge of which is essential for understanding climate variability and global warming but which previously has been extremely difficult to observe reliably on a global scale. MLS is unique in its ability to provide these measurements in the presence of tropical cirrus, where important processes affecting climate variability occur. MLS also provides unique measurements of cirrus ice content. The simultaneous MLS measurements of upper tropospheric water vapor, ice content, and temperature, under all conditions and with good vertical resolution, will be of great value for improving our understanding of processes (such as El Niño) affecting the distribution of atmospheric water, climate variability, and tropospheric-stratospheric exchange. The simultaneous measurements of dynamical tracers CO and N2O enhance the value of this data set by helping identify source regions of the air masses being observed.

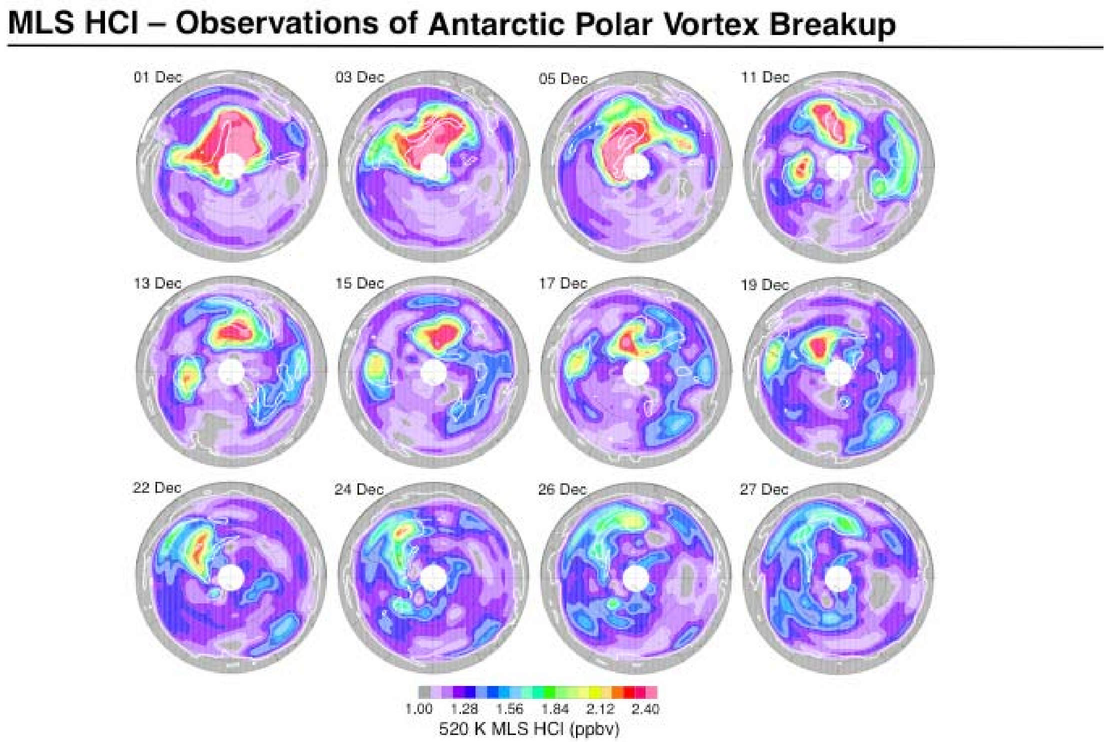

Figure 3. Maps of MLS HCl in the lower stratosphere (520 K, 20 km) detailing the springtime breakup of the 2004 Antarctic vortex. The vortex broke into several fragments between 5 and 11 December, and the evolution and erosion of those fragments is shown through late December, when only one weak fragment remains. After chlorine deactivation by early October, high vortex HCl and very strong HCl gradients across the vortex edge make it an excellent tracer of vortex evolution and morphology.

The MLS instrument was turned on shortly after launch because there is no requirement for outgassing. The MLS team was able to produce data within 15 days of launch. Figure 3 shows Antarctic HCl measurements made shortly after launch as it evolved during the break up of the Antarctic vortex. MLS is discussed in more detail in Waters et al. (this issue).

3.3 OMI

The OMI instrument is a contribution of the Netherlands's Agency for Aerospace Programs (NIVR) in collaboration with the Finnish Meteorological Institute (FMI) to the EOS Aura mission. OMI will continue the TOMS record for total ozone and other atmospheric parameters related to ozone chemistry and climate. OMI measurements will be highly synergistic with the other instruments on the EOS Aura platform. The OMI instrument employs hyperspectral imaging in a push-broom mode to observe solar backscatter radiation in the visible and ultraviolet. The Earth will be viewed in 740 wavelength bands along the satellite track with a swath large enough to provide global coverage in 14 orbits (1 day). The nominal 13 x 24 km spatial resolution can be zoomed to 13 x 13 km for detecting and tracking urban-scale pollution sources. The hyperspectral capabilities will improve the accuracy and precision of the total ozone amounts and will also allow for accurate radiometric and wavelength self calibration over the long term. Aside from the measurements listed in Table 1, the OMI instrument will distinguish between aerosol types, such as smoke, dust, and sulfates, and can measure cloud pressure and coverage, which provide data to derive tropospheric ozone. A combination of algorithms including TOMS version 7, differential optical Absorption Spectroscopy (DOAS), hyperspectral BUV retrievals and forward modeling will be used together to extract the various OMI data products.

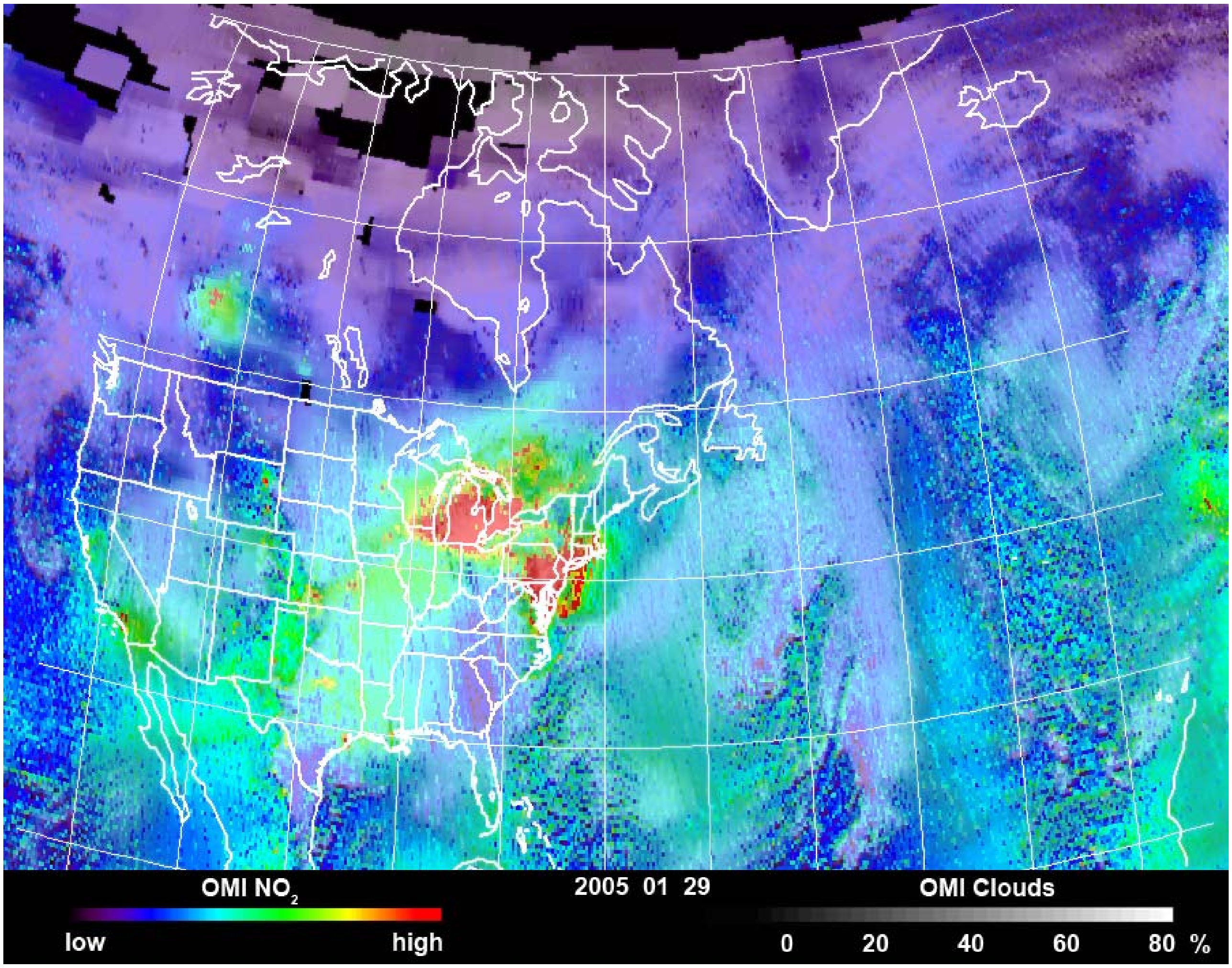

Figure 4. NO_2 measured by the OMI instrument on January 29, 2005. Red indicates high values, blue low values. Clouds are indicated in white. During this period, an air quality alert was issued for the state of Michigan.

After an outgassing and cool down period, OMI began to produce data in October, 2004. Figure 4 shows NO_2 produced by the OMI science team. Further discussion of the OMI instrument is given by Levelt et al. (this issue).

3.4 TES

TES is a high-resolution infrared-imaging Fourier transform spectrometer with spectral coverage of 3.2 to 15.4 µm at a spectral resolution of 0.025 cm^{-1}, thus offering line-width-limited discrimination of essentially all radiatively active molecular species in the Earth's lower atmosphere [Glavitch and Beer, 1991]. TES has significantly more the spectral resolution of the AIRS instrument being flown aboard EOS Aqua. TES has the capability to make both limb and nadir observations. In the limb mode, TES has a height resolution of 2.3 km, with coverage from 0 to 34 km. In the down looking modes, TES has a spatial resolution of 0.53 x 5.3 km with a swath of 5.3 x 8.5 km. TES is a pointable instrument and can access any target within 45° of the local vertical, or produce regional transects up to 885-km length without any gaps in coverage. TES employs both the natural thermal emission of the surface and atmosphere and reflected sunlight, thereby providing day-night coverage anywhere on the globe. TES operates in a combination of limb and nadir mode (called global survey mode) every other. On alternate days, TES does special observations including "step and stare" mode and assessment of special targets like volcanoes. In the global survey mode, TES will provide global maps of tropospheric ozone and its photochemical precursors such as the other measurements are listed in Table 1.

Because TES retrieves the entire spectrum from 3.2 to 15.4 µm, the opportunity exists for TES to make measurements of a large number of other gases (i. e. ammonia and organics). Although the retrieval of these gases will be done in a research mode, the existence of this capability provides a resource for the tropospheric chemistry community.

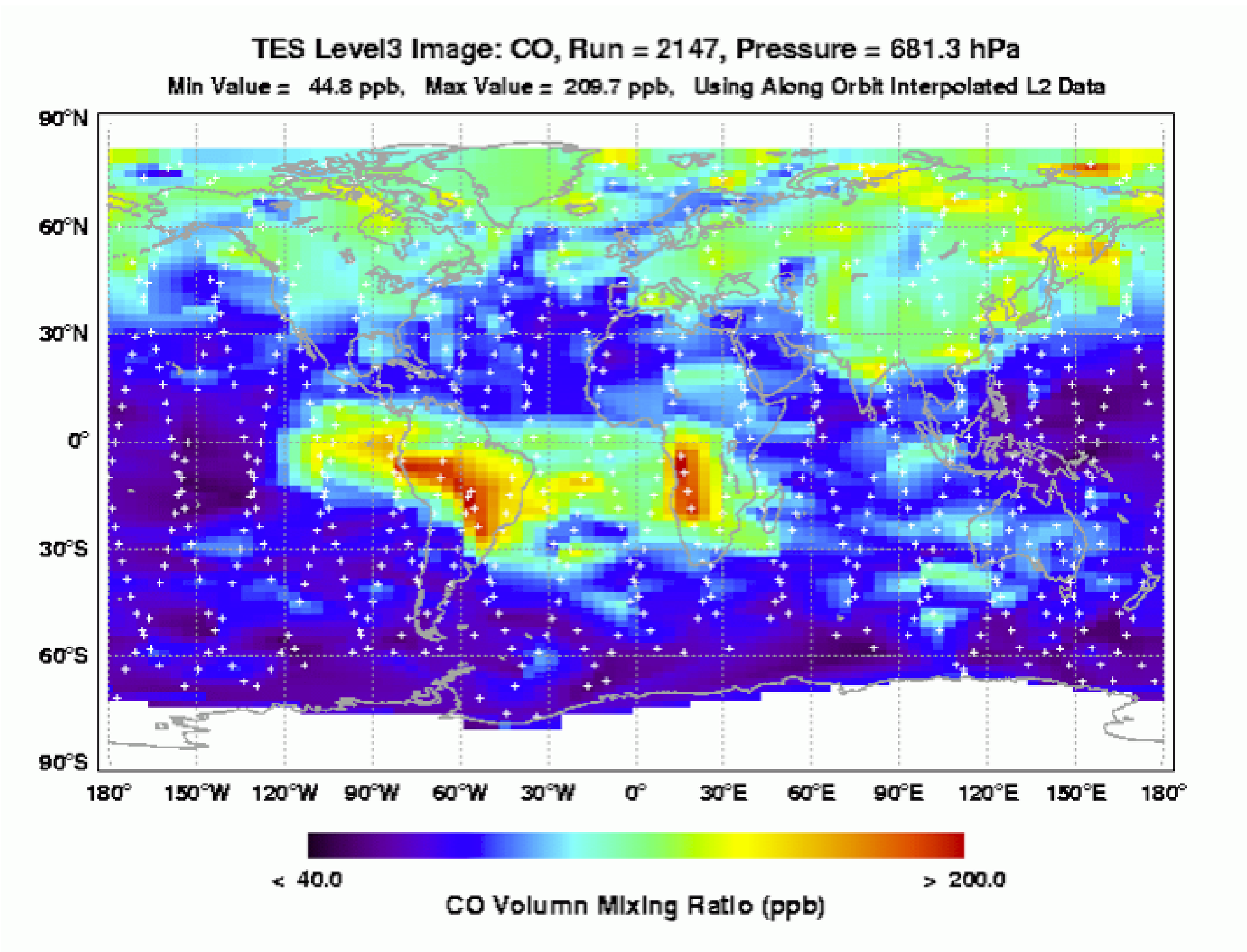

Figure 5 TES CO at lower tropospheric pressure levels from their global survey mode. Measurements are made at the white crosses. Northern hemispheric fossil fuel combustion sources and tropical biomass burning can be seen at lower levels

After launch, TES went through a lengthy outgassing procedure to minimize the ice build up on their cold detectors. Initial results from TES are shown in Figure 5. After several seven months of operation, the translator mechanism (which moves the optical system) began to show signs of bearing wear. The TES Instrument Team has commanded the instrument to skip the limb sounding modes. This will increase the bearing life of the translator and the life of the instrument. In any event, both HIRDLS and MLS provide limb measurement products redundant to TES. Further information on the TES instrument can be found in Beer et al. (this issue).

3.5 Instrument synergy

MLS will provide high vertical resolution profiles which are nearly simultaneous with the OMI observations, and which extend down to and below the tropopause. Thus it will be possible to combine observations from these three instruments with meteorological data to produce effective separation of the stratospheric component of the total column ozone and thus provide an estimate of the tropospheric ozone column (sometimes called the residual). The residual can be compared to TES tropospheric profiles of NO_2 and O_3. The combination of instruments will make it possible to understand the stratospheric and tropospheric contributions to O_3 as well as the transport, physical and chemical processes which effect their distributions.

Because HIRDLS and MLS are both observing the stratosphere, it will also be possible to better interpret photochemical processes involving constituents measured nearly simultaneously by HIRDLS and MLS. For example, HNO_3, OH, NO_2 and N_2O_5 are related through their principal production and loss processes throughout the stratosphere. MLS will measure OH and HNO_3. HIRDLS will measure HNO_3, NO_2 and $N2O_5$. A second example involves chlorine species. Related gases are HCl, $ClONO_2$, ClO, NO_2, and O_3 (which controls the relative concentrations of HCl and $ClONO_2$). Here, $ClONO_2$, NO_2 and O_3 are measured by HIRDLS, and HCl, ClO, and O_3 are measured by MLS. Combining such observations to make important tests of chemical processes on the global scale has been successful using CLAES, MLS, and HALOE on UARS.

3.6 Synergy with Aqua, PICASSO, and Cloudsat

The Aura spacecraft will be flown 15 minutes behind the Aqua spacecraft which means that many of the measurements on Aura will be made shortly after EOS Aqua. About 1 minute behind the Aqua spacecraft, CloudSat and PICASSO/CENA will make measurements of cloud properties using active radar and lidars, respectively. Because MLS is a limb sounder and is observing on the front of the Aura spacecraft, MLS measurements are effectively only ~7 minutes behind those being made by the Aqua nadir sounders. The MLS measurements of upper tropospheric water vapor and temperature in the limb [Read et al., 1995] will be very complimentary to those made by AIRS and AMSU aboard Aqua.

4.0 Summary

The EOS Aura mission was successfully launched on July 15, 2004. With the exception of HIRDLS, all of the instruments are functioning as designed. The measurements being made by Aura will provide the next level of measurements needed by the stratospheric and tropospheric community to advance the science and to answer the crucial broad questions: Is the stratospheric ozone layer recovering? How is the chemistry of the troposphere changing? Although there are only four instruments on Aura, they will provide the needed sets of measurements to answer these broad questions. Furthermore, the breadth of these instrument capabilities will allow us to use Aura data to attack on future science questions.

For more information on the Aura platform and instruments, please refer to the web site http://aura.gsfc.nasa.gov . A pre-launch version of this paper was published in EOS [Schoeberl et al., 2004].

5.0 References

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